A Case Study of Antarctic Katabatic Wind Interaction with Large-Scale Forcing*

THOMAS R. PARISH

Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming

DAVID H. BROMWICH

Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, Columbus, Ohio

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ABSTRACT

Surface pressure decreases of up to 20 hPa occurred over much of the Antarctic continent during a 4-day midwinter period of 1988. The widespread change in the pressure field accompanied intense cyclonic activity to the north of the ice sheet. The equatorward mass transport across the Antarctic coastline resulted in a redistribution of atmospheric pressure that extended to the subtropics of the Southern Hemisphere. Most of the mass flux from Antarctica was the result of low-level processes and appears tied to the katabatic wind circulation. The observed surface pressure decrease over the continent reflects a perturbation of the mean meridional circulation between Antarctica and the subpolar latitudes by synoptic-scale processes. Zonally averaged circulations over Antarctica were examined using output from the European Centre for Medium-Range Weather Forecasts model. Results suggest that only a poorly defined return branch of the meridional circulation exists in the middle and upper troposphere. This southward-directed flow does not compensate for the northward mass transport provided by the katabatic wind outflow in the lower atmosphere. Isallobaric contours over the Antarctic ice sheet roughly match the area of the large-scale drainage catchment associated with katabatic wind transport through the Ross Sea sector. An intense extratropical cyclone was present in the circumpolar oceanic belt to the north of the continent. The horizontal pressure gradient associated with the cyclone prompted enhanced drainage off the high interior plateau. The resulting katabatic flow issued from the continent through a narrow corridor across the Ross Ice Shelf and out over the Southern Ocean.

1. Introduction

Katabatic winds are prominent climatological features of the Antarctic boundary layer. These drainage flows result from the diabatic cooling of the sloping ice sheets and attendant establishment of a horizontal pressure gradient force directed downslope. There is an intimate coupling between the katabatic wind regime and the Antarctic orography. The strength of the katabatic wind is dependent on the slope of the ice surface; the strongest drainage flows are situated at the steep coastal terminus of the continent (Fig. 1). Continental-scale drainage streamlines near the surface (e.g., Parish and Bromwich 1987) show that the katabatic flows follow orographic pathways from the interior of Antarctica to the coast. Studies (e.g., Parish 1982; Schwerdtfeger 1984; Wendler and Kodama 1984; Parish and Bromwich 1987; Bromwich 1989) have documented the persistence of this drainage flow pattern. Wind directional constancy, a ratio of the vector wind magnitude to the mean wind speed, is typically around 0.8 or greater over the sloping ice surface. Such high directional constancy values show the wind to be predominantly unidirectional. However, seasonal and synoptic modulation in the intensity of the katabatic wind is frequently observed (e.g., Parish et al. 1993; Bromwich et al. 1993; Wendler et al. 1993). It appears as if the katabatic wind speed displays more sensitivity to the ambient forcing than does the wind direction, which is strongly constrained by topography.

The nearly incessant low-level outflow off the high interior ice domes implies that atmospheric mass is continually being removed from over Antarctica. Continuity requirements dictate that a time-averaged meridional circulation must become established between Antarctica and the subpolar latitudes to replenish the cold air removed via the katabatic wind regime. Time-averaged model results (e.g., Parish and Bromwich 1997) suggest that warmer air originating over the Southern Ocean north of Antarctica rises and moves southward at higher tropospheric levels. Subsidence then takes place over the ice sheets to complete the thermally direct circulation. Such a mean meridional circulation must be most

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Corresponding author address: Dr. Thomas R. Parish, Dept. of Atmospheric Sciences, University of Wyoming, P.O. Box 3038, Engineering Building, Room 6037, Laramie, WY 82071-3038.
E-mail: parish@grizzly.uwyo.edu

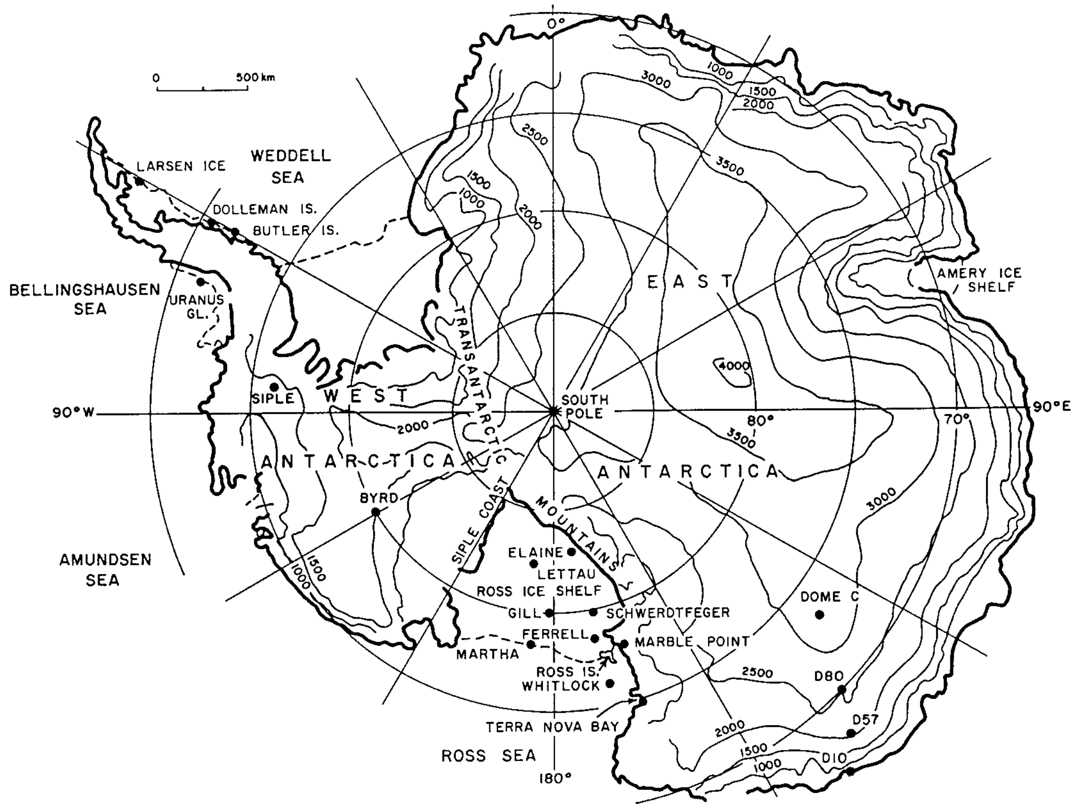

FIG. 1. Antarctic continent with selected geographic references and stations. Terrain contours (m) represented by thin, solid lines.

intense during the nonsummer months when the horizontal temperature gradients over Antarctica are strongest. At these times the katabatic wind regime is most pronounced (Parish and Bromwich 1997). Such a meridional circulation suggests an active mass exchange between Antarctica and subpolar latitudes (Parish et al. 1994).

The purpose of this paper is to examine the interaction of extratropical cyclonic disturbances with the katabatic wind regime over Antarctica. Meridional circulations during a 96-h midwinter period in 1988 produced a widespread and pronounced surface pressure change over the continent. Although observational data from the Antarctic continue to increase (e.g., Keller et al. 1989), spatial coverage is still poor in many regions. Also, the density of upper-air stations remains sparse by midlatitude standards. To avoid difficulties associated with assembling an incomplete observational dataset, numerical model output was used. Such an output set provides full coverage over the continent, and the wind and temperature fields are internally consistent. In this study, analyses are taken from the European Centre for Medium-Range Weather Forecasts model (ECMWF), which provides resolution on 2.5° latitude by 2.5° longitude scales. The gridded output sets were obtained from the National Center for Atmospheric Research ECMWF TOGA (Tropical Oceans and Global Atmosphere) program Archive II. Available automated weather station (AWS) data (Keller et al. 1989) for the midwinter period in question are used to supplement and validate the model output.

2. Rapid pressure change over Antarctica during the winter of 1988

Large seasonal surface pressure changes take place over the Antarctic ice sheet. Such changes are maximized over the high plateau of the Antarctic continent and extend northward to approximately 60°S. Compensating mass changes take place to the north, such that the seasonal pressure change cycle extends into the middle latitudes (see Fig. 6.8 in Schwerdtfeger 1984). The outstanding recurring feature over the elevated plateau region of Antarctica consists of a surface pressure fall during the austral autumn and a pressure rise during the austral springtime. Significant year-to-year variations in amplitude are also present. The isallobaric trends over Antarctica from September to December and again from January to April display a pattern that roughly mirrors the Antarctic ice topography. These surface pressure changes result from the atmospheric adjustment to seasonal changes in diabatic heating (Parish and Bromwich

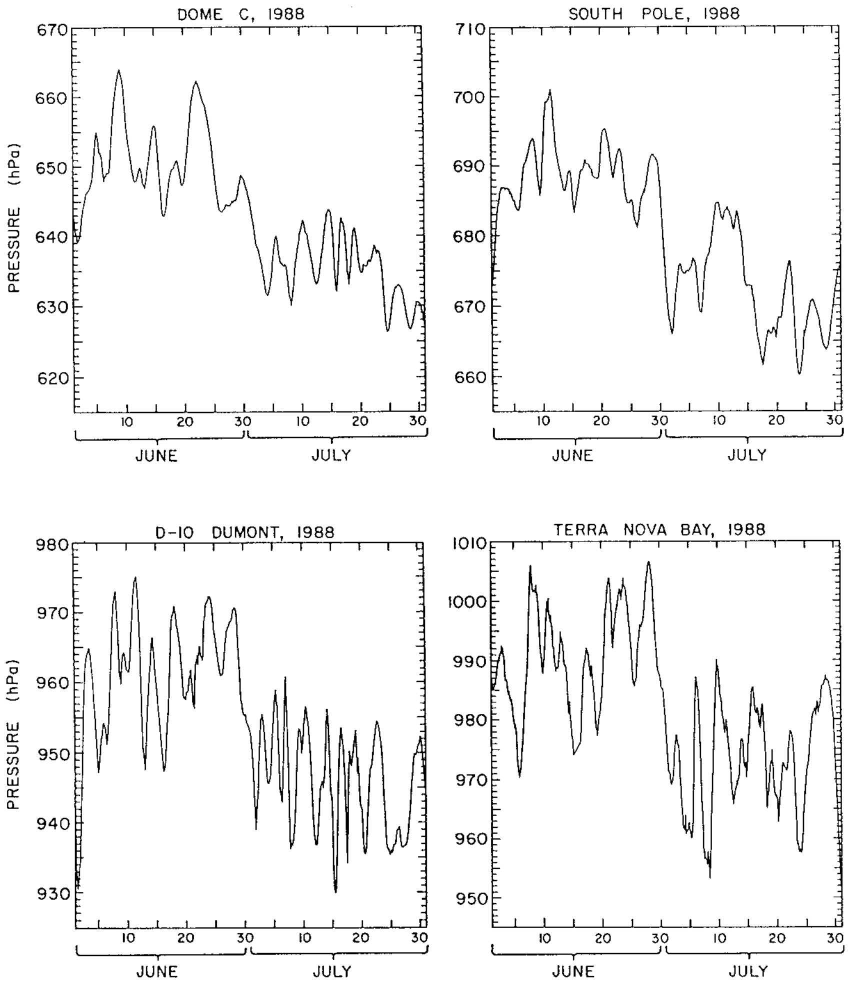

FIG. 2. Time series of 3-h surface pressures for four AWSs from 1 June to 31 July 1988.

1997). This annual cycle is also part of the much-discussed semiannual oscillation in surface pressure over the Antarctic (Schwerdtfeger and Prohaska 1956; Schwerdtfeger 1960, 1967; van Loon 1967; Meehl 1991), in which secondary maxima and minima are present. To the south of approximately 60°S, maximum values of surface pressure are reached during the solstice periods and minima at the equinoxes.

TABLE 1. Mean monthly surface pressure differences (hPa) from June 1988 to July 1988, from available AWS data.

Station	Pressure change	Station	Pressure change
D10	−15.2	Schwerdtfeger	−19.7
D57	−14.1	Terra Nova Bay	−18.0
D80	−13.9	Gill	−18.7
Dome C	−17.3	Elaine	−20.3
Siple	−11.9	Lettau	−20.3
Marble Point	−18.0	Dolleman Island	−13.0
Ferrell	−17.9	Uranus Glacier	−6.3
Whitlock	−16.8	South Pole	−16.0
Martha	−16.3		

Marked and widespread surface pressure changes over Antarctica also occur on shorter timescales. Here we examine an event that occurred during the latter part of June and the first few days of July 1988. Pressure decreases of 20 hPa and larger took place over much of the Antarctic continent. Most of the exhaustion of the continental cold air reserves occurred over a 48-h period. The ''flushing'' of the atmospheric mass from Antarctica during this episode resulted in an extended period of lower than normal surface pressures over the continent. The AWS records for four stations, two situated on the high plateau of Antarctica and two near the coast, for June and July 1988, are shown in Fig. 2. The marked surface pressure change occurred around 30 June. The isallobaric signal is nearly synchronous for the four stations. Surface pressures over much of the continent remain depressed for an extended period. Changes in AWS mean monthly surface pressures from June to July 1988 are shown in Table 1.

Use of the ECMWF output as a means to investigate Antarctic processes presumes that the model represents

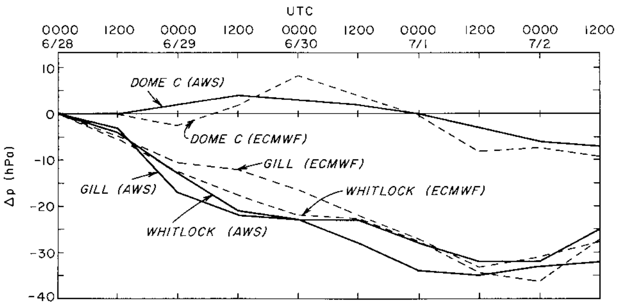

FIG. 3. Surface pressure trends from 0000 UTC 28 June to 1200 UTC 2 July 1988 for AWS units at Gill, Whitlock, and Dome C (solid lines), and corresponding grid locations in ECMWF output set (dashed lines).

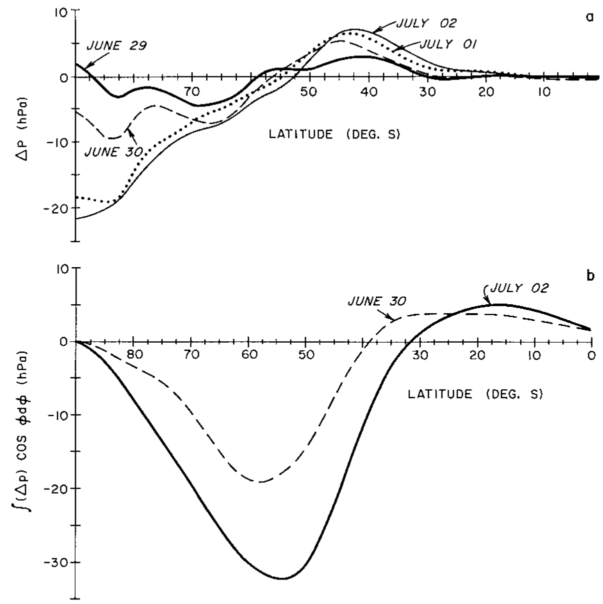

FIG. 4. ECMWF analyses of (a) zonally averaged surface pressure changes from the 0000 UTC 28 June time period. (b) Integrated surface pressure changes from the 0000 UTC 28 June time period starting at South Pole and weighted by cosine of latitude.

the physical world with integrity. Recently, studies have examined the utility of the ECMWF in depicting Antarctic processes. Genthon and Braun (1995) have explored the validity of ECMWF surface output. They show that the model depicts with some fidelity the surface temperatures, precipitation, and accumulation over both Greenland and Antarctica. Bromwich et al. (1995) have also examined the moisture budget of the Antarctic region; they conclude that the ECMWF analyses generally provide reasonable estimates of precipitation over the Antarctic continent. A comprehensive study of model verification over Antarctica by Cullather et al. (1997) has recently been completed. Their results show that the ECMWF compares closely with observational data based on a variety of statistical measures.

To evaluate the ECMWF performance for the period 28 June–2 July 1988, comparison has been made with available AWS data. As an example, Fig. 3 illustrates the surface pressure trends during the period as measured by AWS units at Franklin Island, Gill, and Dome C. The first two are situated within the Ross Sea sector, the third is deployed atop the East Antarctic plateau. Comparison is made with corresponding grid locations from the ECMWF. It is inappropriate to compare actual magnitudes since the orographic representation of Antarctica in the ECMWF differs significantly in some places from the actual terrain. Consequently, only surface pressure differences from the 0000 UTC 28 June 1988 period are plotted. Large-scale pressure changes from the ECMWF are similar to the AWS trends. Some significant differences are apparent and probably reflect the model location of the cyclone centers. Differences are most likely related to the uncertainty in the initial ECMWF analyzed fields, which are obtained from a course observational dataset.

Zonal averages of the ECMWF gridded output for the case study period were first computed, covering the period from 0000 UTC 28 June to 1200 UTC 2 July. Figure 4a illustrates the changes in the ECMWF zonally averaged surface pressures from the 0000 UTC 28 June values for the four subsequent days. The largest surface pressure decreases occur over the Antarctic continent. Zonally averaged surface pressures near the pole show a 20-hPa decrease in the 48-h period from 0000 UTC 29 June to 0000 UTC 1 July. Continuity requirements dictate that the process of mass removal over the Antarctic continent must force compensating surface pressure rises at lower latitudes. This meridional mass exchange extends over a considerable distance as seen in Fig. 4a. Assuming that the Northern Hemisphere (NH) influence is small, the mass transport from Antarctica then is associated with surface pressure changes extending nearly to the subtropics of the Southern Hemisphere (SH).

Mass budget calculations have also been completed, in which the zonally averaged mass changes are weighted by the cosine of the latitude and integrated northward from the South Pole. This provides a more direct evaluation as to the extent of the atmospheric mass redistribution. From 0000 UTC 28 June to 0000 UTC 30 June and 0000 UTC 2 July (Fig. 4b), the maximum transport of mass occurs at approximately 55°S. The response in the mass field implies a corresponding far-field transport that extends north of 40°S, again assuming little influence from the Northern Hemisphere. This offers evidence that the mass exchange across the Antarctic coastline has significant far-field implications.

To obtain some perspective on the time-averaged winter conditions, ECMWF analyses for the 2-month June–July 1988 period were examined. Figure 5a illustrates the streamlines of the mean surface wind over Antarctica during the June–July period based on the 0000 and 1200 UTC ECMWF analyses. The surface streamlines show unequivocally the coupling between the surface wind

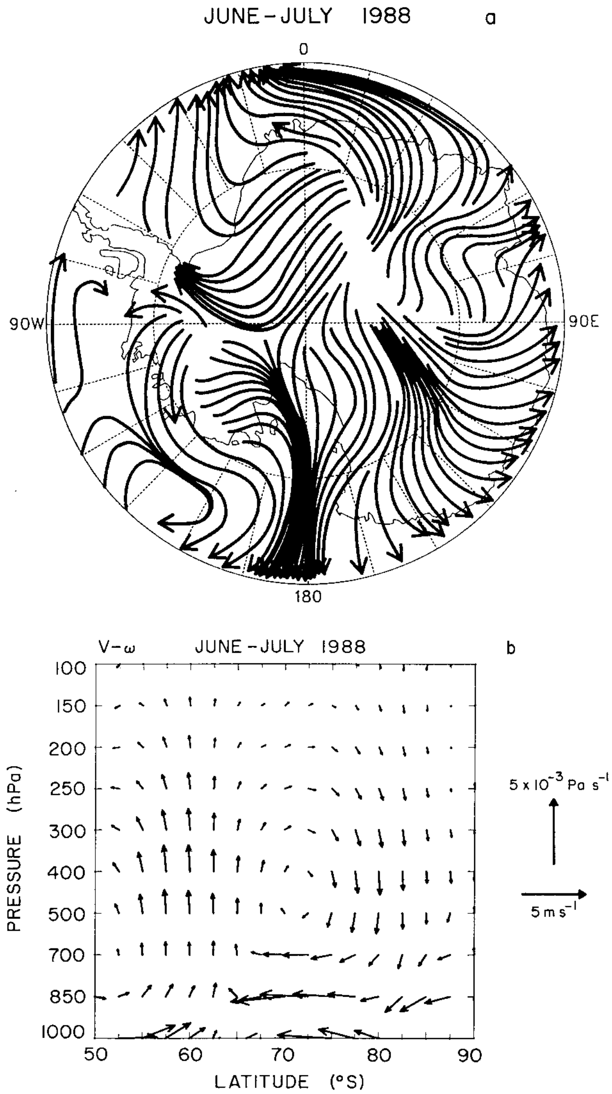

FIG. 5. Mean (a) surface wind streamlines and (b) meridional cross section of v components (m s^{-1}) and vertical velocities (Pa s^{-1} × −1000) in vector form, based on ECMWF 12-h analyses for the 2-month period 1 June–31 July 1988.

regime and the underlying terrain. The surface winds are clearly dominated by the katabatic drainage and follow orographic pathways. To a first approximation, surface winds display a radial drainage pattern off the high interior plateaus. Deviation angles of the flow from the fall line are consistent with expected Coriolis deflection of generally 30°–50°. The intensity of the airflow over the Antarctic continent (not shown) is also related to the terrain slope, and the strongest winds are found near the coastal margin. The ECMWF terrain supports confluence of the katabatic streamlines onto the Ross Ice Shelf, just west of the Amery Ice Shelf, and to the south of the Weddell Sea. Longer time averages, such as the ECMWF 10-yr depiction in Parish and Bromwich (1997), show essentially the same katabatic drainage pattern. The streamline patterns for the individual months of June and July 1988 (not shown) are nearly identical to each other despite the surface pressure differences reported in Table 1. The monthly streamline depictions also broadly match results proposed by Parish and Bromwich (1987) based on a finescale representation of the continent. Such results suggest that the continental-scale katabatic wind regime is an extremely robust feature of the Antarctic boundary layer.

The large-scale drainage pattern in Fig. 5a is inherently divergent. Increasing surface wind speeds from the gently sloping interior to the more steeply sloping coastal ice margin, coupled with the radially diffluent drainage pattern, depict a divergent near-surface environment. Such a divergent low-level wind regime requires upper-level convergence to maintain continuity. The resulting meridional circulation between Antarctic and subpolar latitudes is readily depicted in time-averaged circulations from the ECMWF output. As an example, Fig. 5b illustrates the ECMWF mean June–July 1988 meridional isobaric cross section of the v component of motion and vertical velocity field. Relatively intense, although shallow, low-level northward-directed outflow, which represents primarily the katabatic wind regime, is present with a broad, weak return flow aloft. Large-scale subsidence occurs over the Antarctic continent, which feeds the lower branch of the circulation including the katabatic wind regime. The rising branch extends from the Antarctic coast to the midlatitudes and reflects cyclone activity. However, rising motion near the continent is forced in part by the convergence of the katabatic airstream. As the drainage flows outrun the dynamic support of the sloping terrain, deceleration occurs just offshore of the coastline. The boundary of the secondary circulation appears at the mean position of the Antarctic coastline. Orography appears to be critical in the meridional mass exchange.

Conceptually, changes in the atmospheric mass loading over the Antarctic continent reflect imbalances in the meridional mass exchange. For the zonally averaged pressures to decrease as shown in Fig. 4a, the northward transport of mass in the lower levels must exceed the mid- and upper-tropospheric southward transports. To quantify such conceptual arguments, ECMWF transports for the 4-day period, 28 June–2 July, were examined. As an example, Fig. 6 illustrates the streamlines of the mean surface wind field during the period. The outstanding feature again is the topographic organization present in the surface wind field. Katabatic drainage follows essentially the same pattern as shown in the mean wintertime pattern (Fig. 5a) and the pattern as suggested in the Parish and Bromwich (1987) mean wintertime simulation. The confluence zone structure is nearly identical to that seen in the mean June–July 1988 pattern with only minor differences in the streamline orientation. This again emphasizes the strong topographic control of the Antarctic ice sheets on the surface wind field.

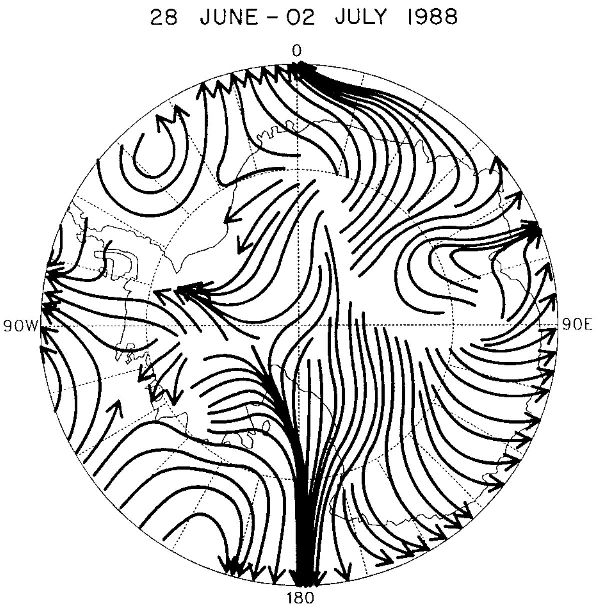

FIG. 6. Mean streamlines of the surface wind, based on ECMWF 12-h analyses from 0000 UTC 28 June to 0000 UTC 2 July 1988.

Diagnosis of the mass balance is difficult due to the compensating nature of the atmosphere. Low-level katabatic outflow is almost exactly matched by the broad upper-level inflow. The small differences in mass transport are masked in the ECMWF analyses owing to the isobaric interpolation of the original spectral representation. However, the mean meridional cross section of the v component and vertical velocity fields (Fig. 7a) for this 4-day midwinter period does show distinct differences from the mean wintertime depiction. The katabatic wind regime is still apparent with strong outflow in the lower levels. Yet the return flow toward Antarctica that is obvious in Fig. 5b is nearly absent. Mean meridional components in the middle and upper troposphere from the subpolar latitudes to the pole are quite small. Differences between the ECMWF 12-h isobaric output from 0000 UTC 28 June–1200 UTC 2 July 1988 and the mean June–July values are illustrated in Fig. 7b. The depiction reveals a circulation opposite to the mean June–July pattern, although differences in the lower-level meridional components over Antarctica are weak. The conceptual picture that can be drawn from Fig. 7 is that the meridional circulation during this 4-day period has been perturbed significantly. Changes are most pronounced at mid- to upper-tropospheric levels. The net effect is that the northward transport at low levels from the katabatic outflow is not compensated by inflow at upper levels. Observed surface pressure changes over the continent seem to match this simple idea.

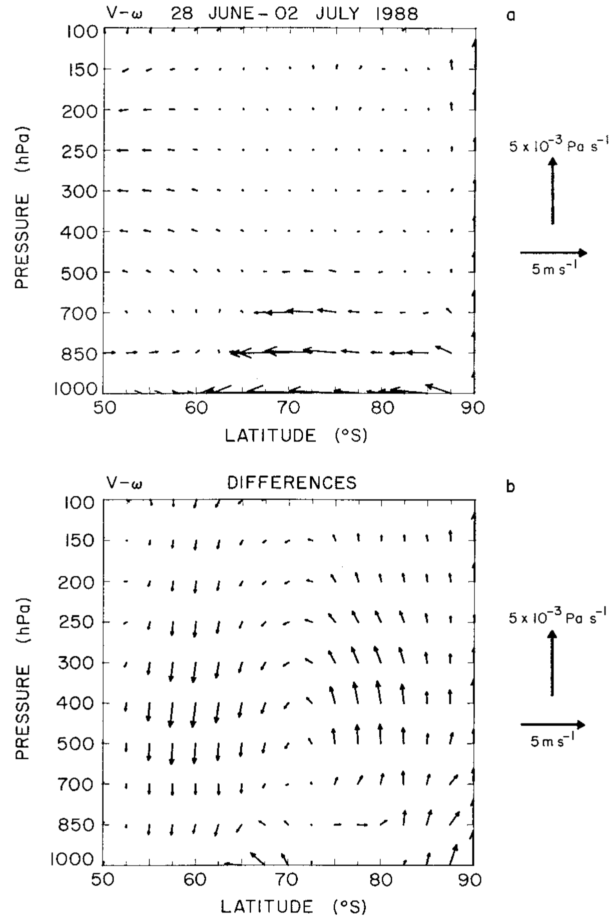

FIG. 7. (a) Mean meridional cross section of v components (m s^{-1}) and vertical velocities (Pa s^{-1} $\times$ -1000) in vector form, based on ECMWF 12-h analyses from 0000 UTC 28 June to 0000 UTC 2 July 1988. (b) Mean vector differences from the mean June–July 1988 representation in Fig. 5b.

3. The synoptic environment 28 June–2 July 1988

Figure 8 illustrates the 0000 UTC sea level pressure over the high southern latitudes from the ECMWF analyses for four consecutive days commencing 28 June 1988. No analyses are attempted over the ice sheet. Errors in reduction to sea level result in anomalously high values of sea level pressure over the elevated plateau regions. The synoptic environment consists of several large cyclonic disturbances about the periphery of the Antarctic continent. The major feature at the 0000 UTC 28 June period is the intense extratropical disturbance north of the Ross Ice Shelf. Other cyclonic disturbances of note were situated north of the Amery Ice Shelf and along the Greenwich meridian. Two weaker cyclonic circulations are seen to the north of Antarctica at 145°E and 70°W. The influence of the three major cyclonic disturbances extends over large geographical areas and reaches the coastal slopes of Antarctica.

Exhaustion of the cold-air reserves over the Antarctic continent commenced approximately 0000 UTC 29 June. The cyclone north of the Ross Sea sector tracks in a predominantly southerly direction. By 0000 UTC 1 July the cyclone center was situated in the eastern

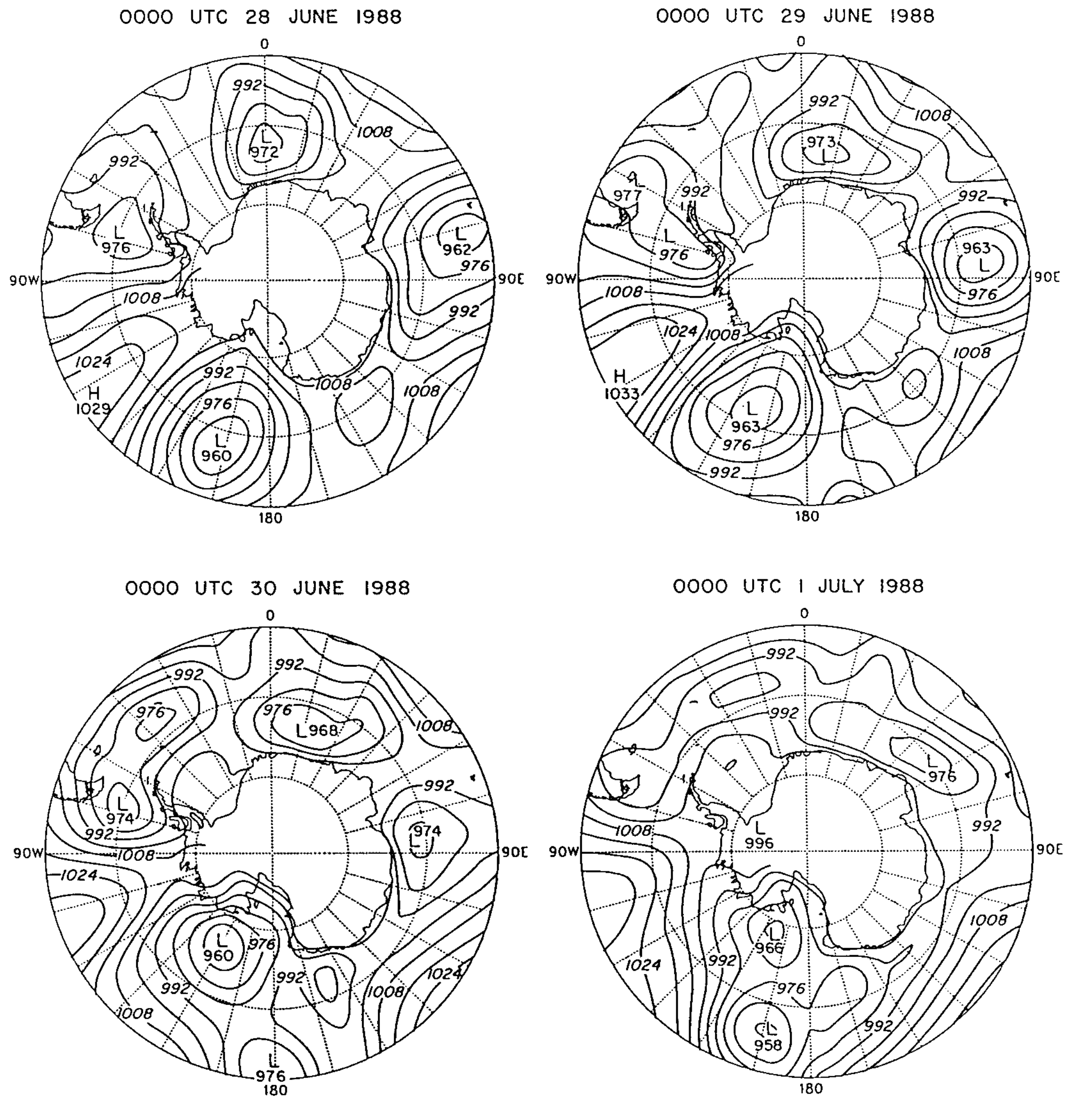

FIG. 8. Sea level pressure analyses 0000 UTC 28 June to 0000 UTC 1 July 1988, based on ECMWF analyses.

Ross Sea within a few hundred kilometers of the West Antarctic coast. Throughout this 48-h period, the horizontal pressure field associated with the cyclone supports a katabatic surge through the Ross Sea corridor. Such katabatic flows have been documented previously (Bromwich et al. 1992; Bromwich et al. 1994; Breckenridge et al. 1993). The Ross Sea sector is a favored climatological northward transport channel for cold air. Other cyclone centers have propagated eastward and southward such that they are also able to tap more efficiently the cold air supply from atop the Antarctic continent.

Figure 9 shows the surface wind vectors at the 0000 UTC periods for 28–30 June and 1 July. The surface winds north of Antarctica reflect the synoptic environment over the Southern Ocean and are dominated by the cyclonic disturbances. The surface winds over the continent, however, display evidence of the mean climatological pattern as shown in Parish and Bromwich (1987). Subtle changes in the katabatic wind regime can be seen over the South Polar plateau region. There is an enhancement of the drainage flows adjacent to the pole from 0000 UTC 28 June to 0000 UTC 30 June. Inspection of wind vectors atop the central plateau of East Antarctica suggests directional changes in the airflow as well. From 28 June to 1 July, directional changes in excess of 90° are apparent over the highest portion of the ridge with drainage clearly influenced by the cyclone in the Ross Sea sector. The outstanding features of the 0000 UTC 30 June wind vectors are the intensity and organization of the cold air transport onto the Ross Ice Shelf. Confluence of the drainage currents occurs over the southern Ross Ice Shelf. In addition, the drainage area feeding onto the Ross Ice Shelf increases

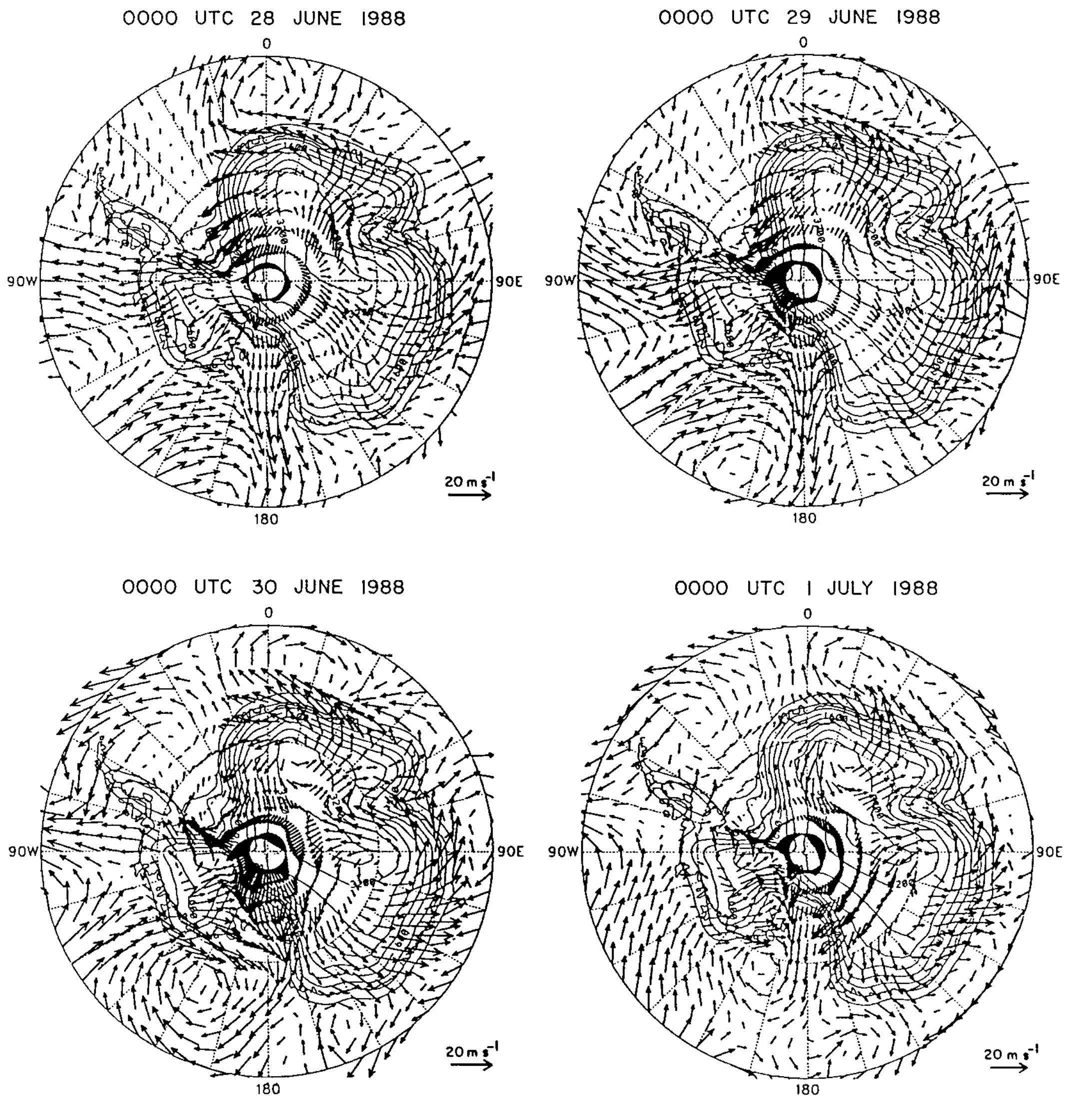

FIG. 9. Surface wind vectors at 0000 UTC 28 June–0000 UTC 1 July 1988, based on ECMWF analyses.

throughout the period. By 0000 UTC 1 July, approximately one-third the surface area of Antarctica appears to drain through the Ross Ice Shelf corridor. Clearly this channel supports the bulk of the cold air transport from the Antarctic continent. Although the large-scale drainage pattern over Antarctica retains much of its climatological character, the regional modulation of the drainage flows is significant and contributes to the mass transport from Antarctica.

It is interesting that the most notable modulation of the katabatic wind regime occurs over the gently sloping continental interior. The coastal region of the East Antarctic continent experiences the strongest synoptic forcing, and yet Fig. 9 suggests only minor directional change throughout the 4-day period. There do appear to be some significant changes in the intensity of the near-coastal drainage flows, especially along approximately 15° and 120°E from 28 to 30 June. Yet, the large-scale direction of the drainage patterns near the continental rim reflects climatology. Previous studies (i.e., Ball 1960) have suggested that the intensity of katabatic winds over the Antarctic coast is modulated by the passage of cyclones. Modeling work (Parish et al. 1993) also suggests that katabatic winds can be influenced by the ambient pressure field. Thus, it is to be expected that the surface winds would be enhanced on the western side of the low pressure trough and diminished on the eastern side. Figure 9 shows a distinct organization of surface winds near the Antarctic coast toward the western side of cyclones. However, the katabatic winds situated to the east of the cyclone centers are not noticeably weakened by the ambient pressure field. Distinct lines of convergence between the katabatic wind and ambient flow around the low are present along the eastern half

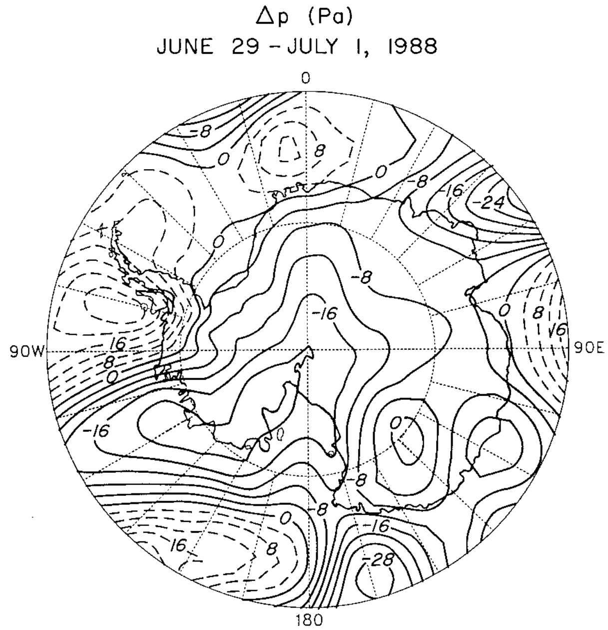

FIG. 10. Surface pressure changes (hPa) from 0000 UTC 29 June 1988 to 0000 UTC 1 July 1988, based on ECMWF analyses. Solid lines refer to surface pressure falls, dashed lines pressure rises.

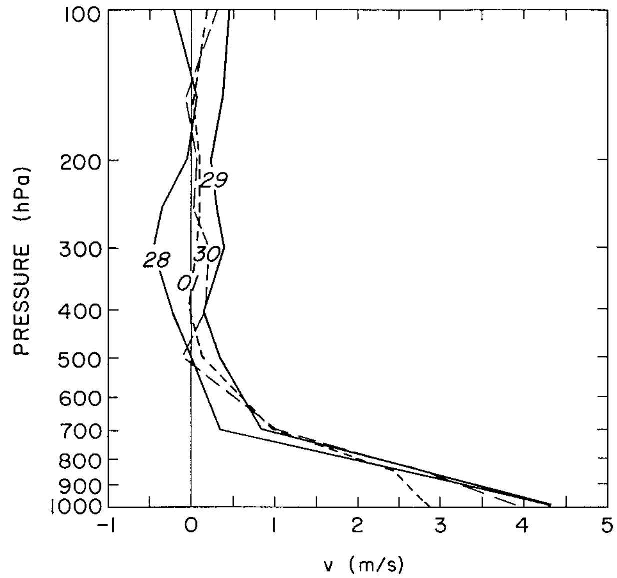

FIG. 11. Zonally averaged v components of motion at 70°S at 0000 UTC 28–30 June and 1 July 1988, from ECMWF analyses.

of the cyclonic circulation situated offshore from the continent. This model-simulated behavior of the katabatic wind near the coast of Antarctica matches the plethora of observations that suggest that, except on rare occasions, the synoptic environment is unable to overcome the topographic forcing at the steep coastal slopes.

Modulation of the direction and speed of the katabatic wind regime over the continent, as seen in Fig. 9, has implications on the transport of mass across the continental coastline. Figure 10 illustrates the surface isallobars from 0000 UTC 29 June to 0000 UTC 1 July, the period of the most intense Antarctic surface pressure changes. The large values over the ocean to the north of the continent reflect primarily the movement of the individual cyclone centers. Pressure changes over the Antarctic continent reflect a net mass outflow across the continental coastline. Surface pressure falls in excess of 12 hPa occur during the 48-h period over a broad sector of the continent. Values approaching 20 hPa are found upslope from the Ross Ice Shelf. There is an association between the isallobaric pattern in Fig. 10 and the katabatic drainage network over the continental interior. The area of the cold air drainage catchment upwind of the Ross Ice Shelf can be inferred from the 0000 UTC 30 June wind vectors in Fig. 9. Notice that the shape of this drainage network broadly matches the isallobaric contour pattern. Regions of largest pressure falls coincide with the drainage through the Ross Ice Shelf corridor.

This relationship seems more than coincidental. There is no doubt that the bulk of the northward mass transport occurs via the low-level wind field. To illustrate, Fig. 11 depicts the 0000 UCT ECMWF zonally averaged meridional components at 70°S for four consecutive days starting 28 June. Each profile displays a maximum meridional wind component at the surface with values between 3 and 4 m s^{-1}. The magnitude of the v component rapidly decreases with height, such that, by 500 hPa it is near zero. Subtle differences between the profiles can be detected in the upper troposphere. The 0000 UTC 28 June profile suggests a distinct return flow above 500 hPa extending past 250 hPa. This matches the conceptual picture of the mean meridional circulation alluded to previously. The 0000 UTC profiles for 29 and 30 June and 1 July show this return flow to be conspicuously absent and a net northward transport is implied. Modulation of the mean meridional circulation is consistent with the observed surface pressure tendency over the Antarctic.

Disruption of the mid- and upper-tropospheric meridional return flow components toward Antarctica is no doubt the result of synoptic influences. The upper-level geopotential height and wind patterns show that the circulation pattern reflects the synoptic forcing. Figure 12 illustrates the 300-hPa geopotential heights and wind vectors at 0000 UTC 30 June, the period of maximum surface pressure change, over the high southern latitudes. Inspection of the corresponding surface pressure map in Fig. 8 shows that the wave activity at 300 hPa is a reflection of the various cyclonic disturbances. During the period 28 June–2 July, the outstanding feature at 300 hPa was the development of a strong ridge over portions of West Antarctica. This ridge is seen in Fig. 12a along approximately 100°W and appears linked to the strong cyclonic activity in the eastern Ross Sea. The 300-hPa transport patterns over Antarctica are influenced by this ridge. A large mass flux occurs from the interior of East Antarctica, across the pole, and exiting the continent near 75°W. The development of the ridge is coincident with the surface pressure changes in the Ross Sea sector. The strong northward transport over West Antarctica shown in Fig. 12b is the most significant feature in the 300-hPa wind field. The disruption of the mean meridional wind components shown in Fig. 7a is no doubt related to this feature.

4. Summary and discussion

Synoptic events during late June and early July of 1988 resulted in a broadscale decrease in surface pressure over much of the Antarctic continent. This event is an example of how cyclonic disturbances can influence the large-scale meridional mass exchange between Antarctica and middle latitudes in the SH. The mass transport from Antarctica occurs primarily at low levels, mostly through the katabatic wind regime. Disruption of the mass transports in the middle and upper troposphere also occurred during this period; the return flow onto the continent was unable to compensate for the low-level northward mass flux. The isallobaric pattern over the continent is coherent with the underlying ice terrain. Given the reduced inflow at upper levels, changes in atmospheric mass loading over Antarctica are linked to the katabatic drainage.

Results also reconfirm the importance of the Antarctic ice topography in shaping the surface wind field over Antarctica. The patterns of cold-air drainage follow climatologically favored orographic pathways despite the intense cyclonic activity. Throughout the 4-day period, a significant fraction of the radiatively cooled air over the Antarctic plateau becomes transported through the Ross Ice Shelf corridor. This is a common occurrence, as shown by previous work (Carrasco and Bromwich 1993; Bromwich 1992; Bromwich et al. 1992). The stream of cold continental air may enhance the baroclinic structure of the cyclonic environment. Such katabatic transport processes may have climatological importance. Mean sea level pressure maps show a low pressure center in the eastern Ross Sea (e.g., Schwerdtfeger 1984, 122; Tzeng et al. 1994). This reflects the frequent cyclonic activity in this region. This case study is likely representative of many events that take place during the winter period.

We speculate that the katabatic wind pattern over the continent results in climatologically favored positions for cyclones about the continent. Mean wintertime sea level pressure maps show low pressure centers about the periphery of Antarctica near 20°E and near 90°E. Mean winter surface streamlines in Fig. 5a show confluence of the katabatic wind field west of climatological low pressure positions near 90°E (Amery Ice Shelf confluence zone) and near 160°W (Ross Sea confluence zone). Although no obvious confluence feature is apparent in Fig. 5a near 20°E, a confluence zone is seen in the higher-resolution mean winter streamlines proposed by Parish and Bromwich (1987, 1991). In all three regions, the Antarctic ice topography acts as a channel for cold, negatively buoyant air that can feed into cyclones, enhancing the baroclinicity. Baines and Fraedrich (1989) conducted laboratory experiments to show that topographic effects induce stationary eddy formation near the Ross and Weddell seas and the Amery Ice Shelf. Numerical simulations by Parish (1992) also illustrate that low-level cyclonic vorticity becomes established near the Ross Sea and north of the Amery Ice

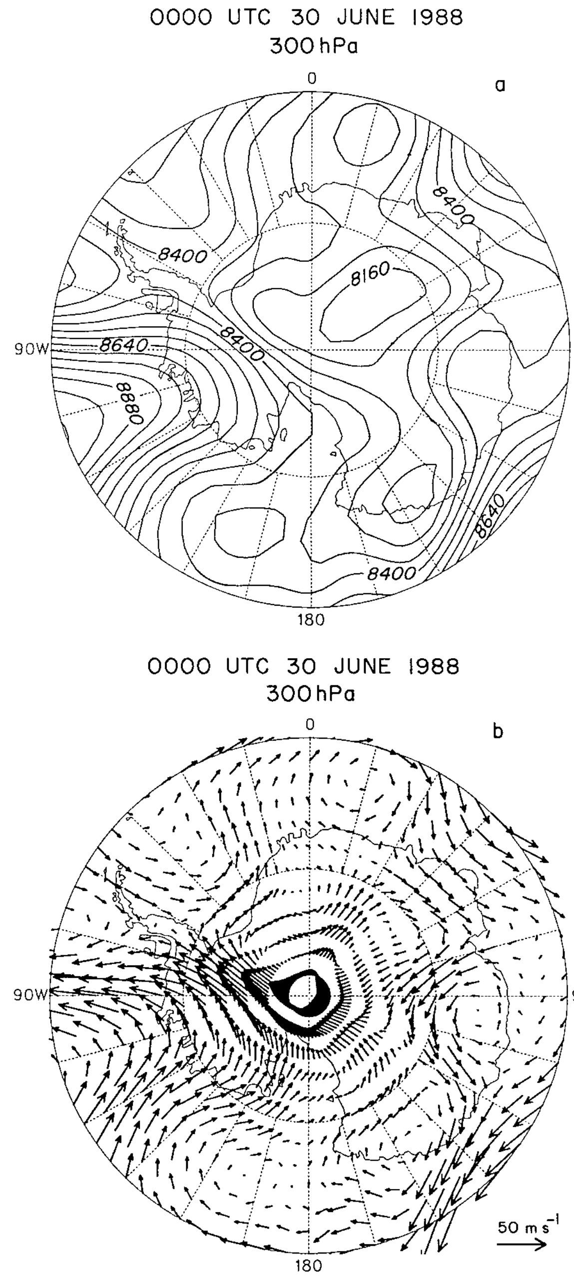

FIG. 12. ECMWF analyses of 0000 UTC 30 June 1988 300 hPa (a) heights and (b) wind vectors.

Shelf. We propose that orographic forcing and the confluence of cold air over the continent in certain coastal regions provide enhanced support for cyclone formation and development.

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